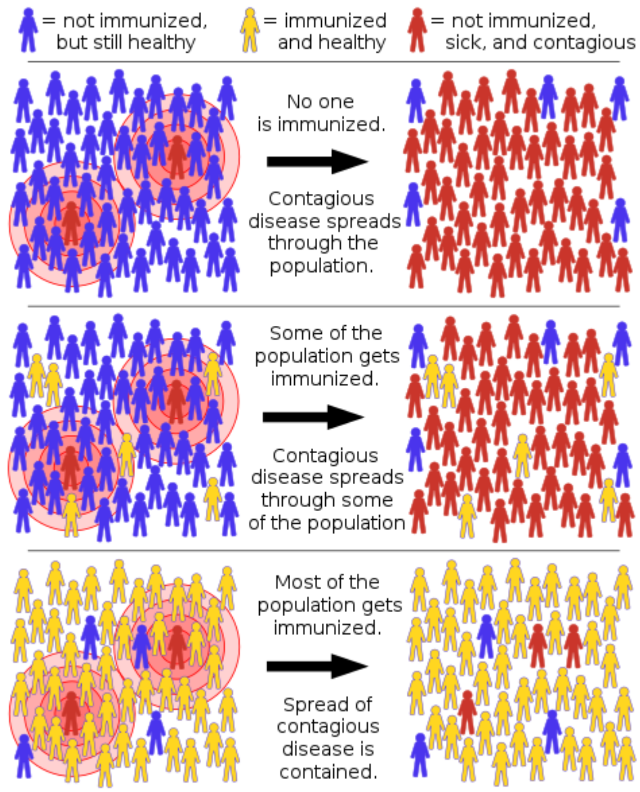
Herd immunity

Herd immunity (also called **herd effect**, **community immunity**, **population immunity**, or **social immunity**) is a form of indirect protection from infectious disease that occurs when a large percentage of a population has become immune to an infection, thereby providing a measure of protection for individuals who are not immune.[1][2] In a population in which a large number of individuals are immune, chains of infection are likely to be disrupted, which stops or slows the spread of disease.[3] The greater the proportion of individuals in a community who are immune, the smaller the probability that those who are not immune will come into contact with an infectious individual.[1]



The top box shows an outbreak in a community in which a few people are infected (shown in red) and the rest are healthy but unimmunized (shown in blue); the illness spreads freely through the population. The middle box shows a population where a small number have been immunized (shown in yellow); those not immunized become infected while those immunized do not. In the bottom box, a large proportion of the population have been immunized; this prevents the illness from spreading significantly, including to unimmunized people. In the first two examples, most healthy unimmunized people become infected, whereas in the bottom example only one fourth of the healthy unimmunized people become infected.

Individual immunity can be gained by recovering from an infection or through vaccination.[3] Some individuals cannot become immune due to medical reasons and in this group herd immunity is an important method of protection.[4][5] Once a certain threshold has been reached, herd immunity gradually eliminates a disease from a population.[5] This elimination, if achieved worldwide, may result in the permanent reduction in the number of infections to zero, called eradication.[6] This method was used for the eradication of smallpox in 1977 and for the regional elimination of other diseases.[7] Herd immunity does not apply to all diseases, just those that are contagious, meaning that they can be transmitted from one individual to another.[5] Tetanus, for example, is infectious but not contagious, so herd immunity does not apply.[4]

The term herd immunity was first used in 1923.[1] It was recognized as a naturally occurring phenomenon in the 1930s when it was observed that after a significant number of children had become immune to measles, the number of new infections temporarily decreased, including among susceptible children.[8] Mass vaccination to induce herd immunity has since become common and proved successful in preventing the spread of many infectious diseases.[9] Opposition to vaccination has posed a challenge to herd immunity, allowing preventable diseases to persist in or return to communities that have inadequate vaccination rates.[10][11][12]

Contents

Effects

Protection of those without immunity

Some individuals either cannot develop immunity after vaccination or for medical reasons cannot be vaccinated.[14][15][4][14] Newborn infants are too young to receive many vaccines, either for safety reasons or because passive immunity renders the vaccine ineffective.[16] Individuals who are immunodeficient due to HIV/AIDS, lymphoma, leukemia, bone marrow cancer, an impaired spleen, chemotherapy, or radiotherapy may have lost any immunity that they previously had and vaccines may not be of any use for them because of their immunodeficiency.[4][14][16][17] Vaccines are typically imperfect as some individuals' immune systems may not generate an adequate immune response to vaccines to confer long-term immunity, so a portion of those who are vaccinated may lack immunity.[1][18][19] Lastly, vaccine contraindications may prevent certain individuals from becoming immune.[14] In addition to not being immune, individuals in one of these groups may be at a greater risk of developing complications from infection because of their medical status, but they may still be protected if a large enough percentage of the population is immune.[4][14][19][20]

Charlotte Cleverley-Bisman, who had all four limbs partially amputated at the age of seven months due to meningococcal disease, a transmissible disease that may be reduced by herd immunity[13]

High levels of immunity in one age group can create herd immunity for other age groups.[7] Vaccinating adults against pertussis reduces pertussis incidence in infants too young to be vaccinated, who are at the greatest risk of complications from the disease.[21][22] This is especially important for close family members, who account for most of the transmissions to young infants.[7][19] In the same manner, children receiving vaccines against pneumococcus reduces pneumococcal disease incidence among younger, unvaccinated siblings.[23] Vaccinating children against pneumococcus

and rotavirus has had the effect of reducing pneumococcus- and rotavirus-attributable hospitalizations for older children and adults, who do not normally receive these vaccines.[23][24][25] Influenza (flu) is more severe in the elderly than in younger age groups, but influenza vaccines lack effectiveness in this demographic due to a waning of the immune system with age.[7][26] The prioritization of school-age children for seasonal flu immunization, which is more effective than vaccinating the elderly, however, has shown to create a certain degree of protection for the elderly.[7][26]

For sexually transmitted infections (STIs), high levels of immunity in one sex induces herd immunity for both sexes.[9][27][28] Vaccines against STIs that are targeted at one sex result in significant declines in STIs in both sexes if vaccine uptake in the target sex is high.[27][28][29] Herd immunity from female vaccination does not, however, extend to homosexual males.[28] If vaccine uptake among the target sex is low, then the other sex may need to be immunized so that that sex can be sufficiently protected.[27][28] High-risk behaviors make eliminating STIs difficult since even though most infections occur among individuals with moderate risk, the majority of transmissions occur because of individuals who engage in high-risk behaviors.[9] For these reasons, in certain populations it may be necessary to immunize high-risk persons or individuals of both sexes to establish herd immunity.[9][28]

Evolutionary pressure

Herd immunity itself acts as an evolutionary pressure on certain viruses, influencing viral evolution by encouraging the production of novel strains, in this case referred to as escape mutants, that are able to "escape" from herd immunity and spread more easily.[30][31] At the molecular level, viruses escape from herd immunity through antigenic drift, which is when mutations accumulate in the portion of the viral genome that encodes for the virus's surface antigen, typically a protein of the virus capsid, producing a change in the viral epitope.[32][33] Alternatively, the reassortment of separate viral genome segments, or antigenic shift, which is more common when there are more strains in circulation, can also produce new serotypes.[30][34] When either of these occur, memory T cells no longer recognize the virus, so people are not immune to the dominant circulating strain.[33][34] For both influenza and norovirus, epidemics temporarily induce herd immunity until a new dominant strain emerges, causing successive waves of epidemics.[32][34] As this evolution poses a challenge to herd immunity, broadly neutralizing antibodies and "universal" vaccines that can provide protection beyond a specific serotype are in development.[31][35][36]

Serotype replacement

Serotype replacement, or serotype shifting, may occur if the prevalence of a specific serotype declines due to high levels of immunity, allowing other serotypes to replace it.[37][38] Initial vaccines against *Streptococcus pneumoniae* significantly reduced nasopharyngeal carriage of vaccine serotypes (VTs), including antibiotic-resistant types,[23][39] only to be entirely offset by increased carriage of non-vaccine serotypes (NVTs).[23][37][38] This did not result in a proportionate increase in disease incidence though since NVTs were less invasive than VTs.[37] Since then, pneumococcal vaccines that provide protection from the emerging serotypes have been introduced and have successfully countered their emergence.[23] The possibility of future shifting remains, so further strategies to deal with this include expansion of VT coverage and the development of vaccines that use either killed whole-cells, which have more surface antigens, or proteins present in multiple serotypes.[23][40]

Eradication of diseases

If herd immunity has been established and maintained in a population for a sufficient time, the disease is inevitably eliminated—no more endemic transmissions occurs.[5] If elimination is achieved worldwide and the number of cases is permanently reduced to zero, then a disease can be declared eradicated.[6] Eradication can thus be considered the final

effect or end-result of public health initiatives to control the spread of infectious disease.[6][7] The benefits of eradication include ending all morbidity and mortality caused by the disease, financial savings for individuals, health care providers, and governments, and enabling resources used to control the disease to be used elsewhere.[6] To date, two diseases have been eradicated using herd immunity and vaccination: rinderpest and smallpox.[1][7][41] Eradication efforts that rely on herd immunity are currently underway for poliomyelitis, though civil unrest and distrust of modern medicine have made this difficult.[1][42] Mandatory vaccination may be beneficial to eradication efforts if not enough people choose to get vaccinated.[43][44][45][46]

A cow with rinderpest in the "milk fever" position, 1982. The last confirmed case of rinderpest occurred in Kenya in 2001 and the disease was officially declared eradicated in 2011.

Free riding

Herd immunity is vulnerable to the free rider problem.[47] Individuals who lack immunity, particularly those who choose not to vaccinate, free ride off the herd immunity created by those who are immune.[47] As the number of free riders in a population increases, outbreaks of preventable diseases become more common and more severe due to loss of herd immunity.[44][46][10][11][12] Individuals may choose to free ride for a variety of reasons, including the perceived ineffectiveness of a vaccine,[48] believing that the risks associated with vaccines are greater than those associated with infection,[1][11][12][48] mistrust of vaccines or public health officials,[49] bandwagoning or groupthinking,[44][50] social norms or peer pressure,[48] and religious beliefs.[11] Individuals are more likely to free ride if vaccination rates are high enough so as to convince a person that he or she may not need to be immune since a sufficient number of others already are.[1][46]

Mechanism

Individuals who are immune to a disease act as a barrier in the spread of disease, slowing or preventing the transmission of disease to others.[3] An individual's immunity can be acquired via a natural infection or through artificial means, such as vaccination.[3] When a critical proportion of the population becomes immune, called the *herd immunity threshold* (HIT) or *herd immunity level* (HIL), the disease may no longer persist in the population, ceasing to be endemic.[5][30] This threshold can be calculated by taking R_0, the basic reproduction number, or the average number of new infections caused by each case in an entirely susceptible population that is homogeneous, or well-mixed, meaning each individual can come into contact with every other susceptible individual in the population,[9][30][43] and multiplying it by S, the proportion of the population who are susceptible to infection:

$$R_0 \cdot S = 1.$$

S can be rewritten as (1 - p) because p is the proportion of the population that is immune and p + S equals one. Then, the equation can be rearranged to place p by itself as follows:

$$R_0 \cdot (1 - p) = 1, \rightarrow 1 - p = \frac{1}{R_0}, \rightarrow p_c = 1 - \frac{1}{R_0}.$$

Estimated R_0 and HITs of well-known infectious diseases[51]

<table>
<tr><th>Disease</th><th>Transmission</th><th>R_0</th><th>HIT</th></tr>
<tr><td>Measles</td><td>Airborne</td><td>12–18</td><td>92–95%</td></tr>
<tr><td>Pertussis</td><td>Airborne droplet</td><td>12–17[52]</td><td>92–94%</td></tr>
<tr><td>Diphtheria</td><td>Saliva</td><td rowspan="2">6–7</td><td rowspan="2">83–86%</td></tr>
<tr><td>Rubella</td><td rowspan="2">Airborne droplet</td></tr>
<tr><td>Smallpox</td><td rowspan="2">5–7</td><td rowspan="2">80–86%</td></tr>
<tr><td>Polio</td><td>Fecal-oral route</td></tr>
<tr><td>Mumps</td><td rowspan="2">Airborne droplet</td><td>4–7</td><td>75–86%</td></tr>
<tr><td>SARS</td><td>2–5[53]</td><td>50–80%</td></tr>
<tr><td>Ebola
(Ebola virus epidemic in West Africa)</td><td>Bodily fluids</td><td>1.5–2.5[54]</td><td>33–60%</td></tr>
<tr><td>Influenza
(influenza pandemics)</td><td>Airborne droplet</td><td>1.5–1.8[52]</td><td>33–44%</td></tr>
</table>

With p being by itself on the left side of the equation, it can now be written as p_c to represent the critical proportion of the population needed to become immune to stop the transmission of disease, or the herd immunity threshold.[9] R_0 functions as a measure of contagiousness, so low R_0 values are associated with lower HITs, whereas higher R_0s result in higher HITs.[30][43] For example, the HIT for a disease with an R_0 of 2 is theoretically only 50%, whereas with disease with an R_0 of 10 the theoretical HIT is 90%.[30] These calculations assume that the entire population is susceptible, meaning no individuals are immune to the disease. In reality, varying proportions of the population are immune to any given disease at any given time.[9] To account for this, the effective reproductive number R_e, also written as R_t, or the average number of infections caused at time t, can found by multiplying R_0 by the fraction of the population that is still susceptible. When R_e is reduced to and sustained below 1, the number of cases occurring in the population gradually decreases until the disease has been eliminated.[9][30][55] If a population is immune to a disease in excess of that disease's HIT, the number of cases reduces at a faster rate, outbreaks are even less likely to happen, and outbreaks that occur are smaller than they would be otherwise.[1][9] If R_e increases to above 1, then the disease is neither in a steady state nor decreasing in incidence but is actively spreading through the population and infecting a larger number of people than usual.[44][55]

A second assumption in these calculations is that populations are homogeneous, or well-mixed, meaning that every individual comes into contact with every other individual, when in reality populations are better described as social networks as individuals tend to cluster together, remaining in relatively close contact with a limited number of other individuals. In these networks, transmission only occurs between those who are geographically or physically close to one another.[1][43][44] The shape and size of a network is likely to alter a disease's HIT, making incidence either more or less common.[30][43] In heterogeneous populations, R_0 is now considered to be a measure of the number of cases generated by a "typical" infectious person, which depends on how individuals within a network interact with each other.[1] Interactions within networks are more common than between networks, in which case the most highly connected networks transmit disease more easily, resulting in a higher R_0 and a higher HIT than would be required in a less connected network.[1][44] In networks that either opt not to become immune or are not immunized sufficiently, diseases may persist despite existing in better-immunized networks.[44]

Boosts

Vaccination

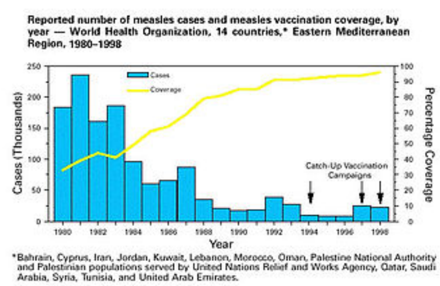
The primary way to boost levels of immunity in a population is through vaccination.[1][56] Vaccination is originally based on the observation that milkmaids exposed to cowpox were immune to smallpox, so the practice of inoculating people with the cowpox virus began as a way to prevent smallpox.[42] Well-developed vaccines provide protection in a far safer way than natural infections, as vaccines generally do not cause the diseases they protect against and severe adverse effects are significantly less common than complications from natural infections.[57][58] The immune system does not distinguish between natural infections and vaccines, forming an active response to both, so immunity induced via vaccination is similar to what would have occurred from contracting and recovering from the disease.[59] To achieve herd immunity through vaccination, vaccine manufacturers aim to produce vaccines with low failure rates and policy makers aim to encourage their use.[56] After the successful introduction and widespread use of a vaccine, sharp declines in the incidence of diseases it protects against can be observed, necessarily decreasing the number of hospitalizations and deaths caused by such diseases.[60][61][62]

Assuming a vaccine is 100% effective, then the equation used for calculating the herd immunity threshold can be used for calculating the vaccination level needed to eliminate a disease, written as V_c.[1] Vaccines are usually imperfect however, so the effectiveness, E, of a vaccine must be accounted for:

$$V_c = \frac{1 - \frac{1}{R_0}}{E}.$$

From this equation, it can be observed that if E is less than $(1 - 1/R_0)$, then it is impossible to eliminate a disease, even if the entire population is vaccinated.[1] Similarly, waning vaccine-induced immunity, as occurs with acellular pertussis vaccines, requires higher levels of booster vaccination to sustain herd immunity.[1][21] If a disease has ceased to be endemic to a population, then natural infections no longer contribute to a reduction in the fraction of the population that is susceptible. Only vaccination contributes to this reduction.[9] The relation between vaccine coverage and effectiveness and disease incidence can be shown by subtracting the product of the effectiveness of a vaccine and the proportion of the population that is vaccinated, p_v, from the herd immunity threshold equation as follows:

$$(1 - \frac{1}{R_0}) - (E \times p_v).$$



Measles vaccine coverage and reported measles cases in Eastern Mediterranean countries. As coverage increased, the number of cases decreased.

It can be observed from this equation that, *ceteris paribus*, any increase in either vaccine coverage or vaccine effectiveness, including any increase in excess of a disease's HIT, further reduces the number of cases of a disease.[9] The rate of decline in cases depends on a disease's R_0, with diseases with lower R_0 values experiencing sharper declines.[9] Vaccines usually have at least one contraindication for a specific population for medical reasons, but if both effectiveness and coverage are high enough herd immunity can protect these individuals.[15][17][20] Vaccine effectiveness is often, but not

always, adversely affected by passive immunity,[63][64] so additional doses are recommended for some vaccines while others are not administered until after an individual has lost his or her passive immunity.[16][20]

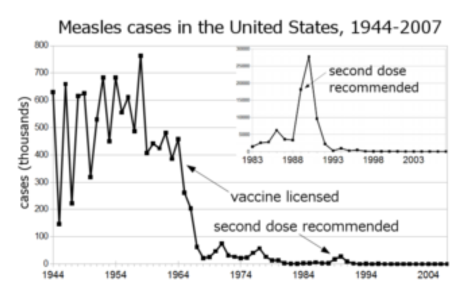
Passive immunity

Individual immunity can also be gained passively, in which antibodies to a pathogen are transferred from one individual to another. This can occur naturally, whereby maternal antibodies, primarily immunoglobulin G antibodies, are transferred across the placenta and in colostrum to fetuses and newborns,[65][66] or artificially, by which antibodies from the serum or plasma of an immune individual are injected into a susceptible person.[59][67] Protection generated from passive immunity is immediate but wanes over the course of weeks to months, so any contribution to herd immunity is temporary.[5][59][68] For diseases that are especially severe among fetuses and newborns, such as influenza and tetanus, pregnant women may be immunized in order to transfer antibodies to the child.[15][69][70] In the same way, high-risk groups that are either more likely to experience infection or are more likely to develop complications from infection may receive antibody preparations to prevent these infections or to reduce the severity of symptoms.[67]

Cost–benefit analysis

Herd immunity is often accounted for when conducting cost–benefit analyses of vaccination programs. It is regarded as a positive externality of high levels of immunity, producing an additional benefit of disease reduction that would not occur had no herd immunity been generated in the population.[71][72] Therefore, herd immunity's inclusion in cost–benefit analyses results in more favorable cost-effectiveness or cost–benefit ratios and an increase in the number of disease cases averted by vaccination.[72] Study designs done to estimate herd immunity's benefit include recording disease incidence in households in which a member was vaccinated, randomizing a population in a single geographic area to be vaccinated or not, and observing disease incidence before and after a vaccination program is introduced.[73] From these, it can be observed that disease incidence may decrease to a level beyond what can be predicted from direct protection alone, indicating that herd immunity contributed to the reduction.[73] When serotype replacement is accounted for, it reduces the predicted benefits of vaccination.[72]

History



Measles cases in the United States before and after mass vaccination against measles began.

The term *herd immunity* was first used in 1923 to refer to an entire population's immunity, in reference to research examining disease mortality in mouse populations with varying degrees of immunity.[74] Herd immunity was first recognized as a naturally occurring phenomenon in the 1930s when A. W. Hedrich published research on the epidemiology of measles in Baltimore and took notice that after many children had become immune to measles, the number of new infections temporarily decreased, including among susceptible children.[8] In spite of this knowledge, efforts to control and eliminate measles were unsuccessful until mass vaccination using the measles vaccine began in the 1960s.[8] Mass vaccination, discussions of disease eradication, and cost–benefit analyses of vaccination subsequently prompted more widespread use of the term *herd immunity*.[1] In the 1970s, the theorem used to calculated a disease's herd immunity threshold was developed.[1] During the smallpox eradication campaign in the 1960s and 1970s, the practice of *ring vaccination*, of which herd immunity is integral to, began as a way to immunize every person in a "ring" around an infected individual to prevent outbreaks from spreading.[75]

Since the adoption of mass and ring vaccination, complexities and challenges to herd immunity have arisen.[1][56] Modeling of the spread of infectious disease originally made a number of assumptions, namely that entire populations are susceptible and well-mixed, which do not exist in reality, so more precise equations have been developed.[1] In recent decades, it has been recognized that the dominant strain of a microorganism in circulation may change due to herd immunity, either because of herd immunity acting as an evolutionary pressure or because herd immunity against one strain allowed another already-existing strain to spread.[32][38] Emerging or ongoing vaccine controversies and various reasons for opposing vaccination have reduced or eliminated herd immunity in certain communities, allowing preventable diseases to persist in or return to these communities.[10][11][12]

See also

- Premunity

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External links

- A visual simulation of herd immunity (http://www.software3d.com/Home/Vax/Immunity.php) written by Shane Killian and modified by Robert Webb